Validating a Physical Model with Real Data
Part I: Verifying Wind Tunnel Flow Features in Equivalent Real-Sized Data

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ABSTRACT

How much realism is enough? Airflow around a single building was simulated in the Environmental Protection Agency [EPA] Wind Tunnel by Snyder and Lawson, and their results were published in 1994. Other researchers have done subsequent simulations in the EPA Wind Tunnel; however, the Snyder and Lawson results were selected for calibration against real air flow measurements acquired around an equivalent single office building in New Mexico. This paper will summarize the Wind Tunnel's miniaturized physical model, the Wind Tunnel results targeted for validation, the field test designed for 'real' air flow sampling, and a comparison of the wind tunnel flow features verses the data acquired around a real single building structure. Six out of six major Wind Tunnel flow features were validated with the 'real' field data. A case study from the 'real' field data demonstrates these features numerically, graphically, and with pictures. Recommendations for future studies will conclude the paper.

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1. Background.

How much realism is enough? Computerized atmospheric models are constructed with a blend of mathematical representations of real-world atmospheric variables, and various assumptions and constraints. Scaled-down physical models such as those used in wind tunnels include major obstacles, a well-defined airflow fields and again, assumptions and constraints. One common constraint of laboratory studies is that the equivalence of ‘atmospheric stability’ is not usually a factor in the wind tunnel design. How close the physical models come to reality is a function of the amount of details included in the model, the model assumptions, and how closely the measurements in the comparison scenario and physical model design, match each other.

In 1994 Snyder and Lawson published a National Oceanic & Atmospheric Administration [NOAA]/EPA Wind Tunnel study which captured the airflow around a miniaturized building of varying dimensions and orientations. Were their results realistic?

In 2003 and 2005, the Army Research Lab [ARL] designed and conducted micrometeorological field studies of airflow about and over a building. One of the primary goals was to verify the EPA Wind Tunnel study results. Without the full Wind Tunnel data set in-hand at the time of the analysis, the validation effort was limited to isolating and identifying repeated airflow patterns occurring within the physical model results and quantifying these features within the field data set. Initially, four airflow features were identified. They consisted of the upwind Fetch Flow, Velocity Acceleration over the Roof, Velocity Deficit and the down-wind Cavity Flow. Two additional features, specifically the Leeside Horizontal Side-Eddies and Leeside Reattachment Zone, were subsequently identified and evaluated from the data set of the latter field study.

In this paper, we will discuss the wind tunnel study in terms of the physical model, the flow features targeted for validation, the field study design and a quantitative analysis of these airflow features. Heavy emphasis is given to the initial four features. Due to page limitations imposed, the later two airflow features are briefly presented in Appendix A.

2. Wind Tunnel’s miniaturized physical model.

The Snyder/Lawson Wind Tunnel study published in 1994 simulated a boundary layer using the Irwin (1981) system of spires and roughness on the floor downwind. The boundary layer depth generated was approximately 2 m deep, with a roughness length of 1 mm. A miniaturized building of 200 mm × 200 mm (cube) was constructed and used as their standard reference. Four measurement series followed: First, the crosswind dimensions of the miniaturized building were increased 2, 4, and 10 times that of the cube. Second, the flow fields were measured behind the buildings with along-wind dimensions of 0.015, 0.5, 1, 2, and 4 times that of the cube. The third series increased the building height to 2 and 3 times that of the cube. The final series of measurements rotated the cube 45 degrees. Velocity measurements were acquired using a pulsed-wire anemometer in the longitudinal and vertical directions. Approximately 300 points in the vertical center-plane both upwind and downwind of the building were sampled.

3. Wind Tunnel Study results targeted for validation.

The Wind Tunnel Study results showed several consistent flow features such as an upstream stagnation point, separation and reattachment streamlines, and a “cavity” flow. The size and dimensions for each of these features varied with the modification of the standard cube and are summarized in Snyder and Lawson (1994).

Since the publication of the Snyder/Lawson study, other flow features were identified and extracted from the original wind tunnel data. These features included Acceleration over the Roof, a Velocity Deficit just lee of the building, a leeside reattachment zone, and leeside horizontal side eddies. (Pardyjak et al, 2004) and (Shinn and Gouveia, 2001)

4. Field test designed for ‘real’ air flow sampling.

The field test design required a site selection, a pre-determined data acquisition time period, meteorological sensor selections, and the defining of a physical layout for the building(s) and sampling sensors. Each of these is summarized below:

4.1 Field study data acquisition site selection and time period.

The site selected for the full-sized building data acquisition was a southwestern U.S.A. desert location. The optimal time period (season) was defined after consulting a twenty-two-year climatology for the region. Just as wind tunnel airflow is strong and consistent, the greatest and most consistent wind magnitudes occurring for the site selected were between March and April. The prevailing wind direction during this ‘windy season’ was westerly (Novlan, 1982).

The diurnal heating effects would potentially complicate the post-test analysis; therefore, a time period minimizing the heating/cooling cycle was sought. Consulting the solar astronomical charts, the data acquisition was chosen to be around the equinox time period (later part of March). Ideally, the solar equinox would provide approximately equal heating/cooling cycles over a 24 hr period for the testing area.

4.2 Meteorological sensor selection.

Two types of sensors were selected for the airflow validation effort. In Phase I (FY2003), the primary interest was to identify the mean airflow features. Therefore, R.M. Young Wind Monitors (vanes with propellers) were selected. These Wind Monitors provided time (decimal hours, Local Time), wind speed (m/s) and direction (degrees). Details of these sensors can be found in Bustillos et al (2006), and Cionco et al (2003).

In Phase II (FY2005), the interest shifted from the mean attributes to the airflow details as turbulent flow characteristics. Therefore, the quicker response-R.M. Young 81000 Ultrasonic Anemometers were selected. Sensor details can be found in Vaucher (2006).

To complete the overall atmospheric characterization around the single building, the thermodynamic conditions and a general environmental description were required. The sensors selected for this general characterization were the same for Phase I and II. That is, a Campbell datalogger linked four sensors quantifying pressure, temperature, relative humidity, and solar radiation. Details can be found in Vaucher (2006).

A variety of mesoscale meteorological charts documented the larger scale atmospheric influences during the data acquisition periods.

4.3 Physical layout.

The Wind Tunnel buildings were categorized by a width to height ratio. The full sized building selected was equated to the appropriate wind tunnel building ratio. Using the results of the wind tunnel, the anticipated flow features were identified (see section 4.4).

The full-sized, two-story, rectangular cement building had a ‘flat’ roof, as did the miniature model equivalent. However, unlike the physical model, the full-sized building had two trees located on the leeside corners, with shrubs lining the leeside. The other three sides were effectively clear of foliage obstacles. Similar buildings surrounded the full-sized building on three sides (north, west, south) with a parking lot on the remaining side (east). The wind tunnel had no neighboring buildings or parking lot, and therefore, was clear of obstacles on all sides.

4.4 Optimal sensor placement.

After identifying the appropriate width/height ratio of the full-sized building and correlating that with the wind tunnel results, the selected flow features were extracted from the wind tunnel streamline charts. These wind features initially [2003-Phase I] included Fetch Flow, Velocity Acceleration over the building, Velocity Deficit, and Cavity Flow. During the *WSMR 2005 Urban Study* (Phase II), the horizontal leeside building eddies, and reattachment zone flow features were added. See Figure 1.

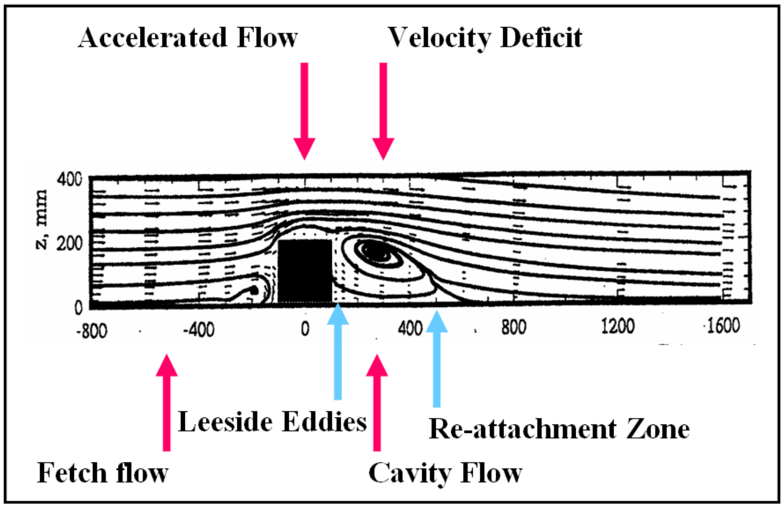

FIGURE 1. Consistent flow features initially identified within the 1994 Snyder/Lawson Wind Tunnel results included the Fetch Flow, the Accelerated Flow over the Roof, the Velocity Deficit and the Cavity Flow. Later, the relative positions of Horizontal Leeside Eddies and the Re-attachment Zone were added to the list of attributes used to verify the physical model

Translating the millimeter scale of the wind tunnel into full-sized dimensions required a common ratio feature, which was the building height. Optimizing the sensor placement required careful observation of the subtle attributes within the published wind tunnel airflow streamlines. Sliding the target tower position forward and aft with respect to the subject building and flow feature, was a process much like manually focusing a telescope for optimum imagery.

A complication in the optimal sensor placement arose when addressing the fact that unlike the wind tunnel's physical model, another building blocked the windward (west) side of the subject building. The prevailing winds for the region and subject building would be from the west (as with the wind tunnel); however, they would have to go around the partial west-side obstruction (building). Therefore, the initial westerly Fetch Flow would have a channeled southwesterly flow approach to the subject building.

Comparing the wind tunnel results for the 45 degree and the 90 degree cube flow, the tower placement most affected would be the leeside (east) tower. This tower placement was intended to document the 'Flow Reversal' or 'Cavity Flow' feature. (Refer to Figure 1.) Therefore, a range of tower placement distances (and angles) was calculated for the leeside (east) tower. (See Table 1.)

For Phase I, four tower positions surrounding the building were selected, with a fifth 5 m tower on the roof. The tower placements are shown in Figure 2 and were calculated as follows:

TABLE 1. Sensor placement for each verification flow feature.

Tower Title/Bldg Side	Distance from Building	Flow Feature Targeted
West Tower	> (3 * z_B)	Fetch Flow
North	(1.0 * z_B)	Channeled Flow
East	(1.5 * z_B) to (2.0 * z_B)	Velocity Deficit and Cavity Flow
South	(1.0 * z_B)	Channeled Flow
Roof	Center of Roof	Flow acceleration

z_B = height of building

NOTE: For convenience, a short-hand notation of tower location and level is utilized in the subsequent text. The interpretation of this shorthand is as follows: Using the subject building as the reference, each tower is labeled by its compass location (Southwest is SW, North is N, Northeast is NE, South is S). The sensor height with respect to the tower's lowest level is hyphenated next to the tower location. For example: 'Roof-4.5 m' means 'Roof Tower at 4.5 m above the roof'; 'SW-10 m' means 'southwest tower at the 10 m AGL'; and 'NE-2 m' means 'northeast tower at 2 m AGL'.

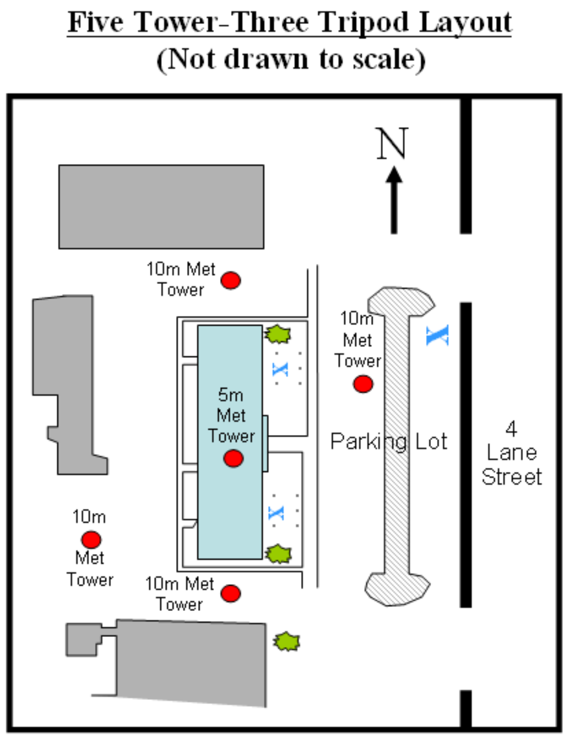

FIGURE 2. Phase I (WSMR 2003 Urban Study) used five tower positions indicated by the red dots. Each tower position was selected to verify a flow feature. In Phase II (WSMR 2005 Urban Study), 2 m-Tripods were added and are labeled with an X. The small dots around the "X" show the flagged fence post configuration. Trees are noted by the jagged green circles.

5. Airflow Feature Characteristics.

The four airflow features identified in the wind tunnel study and identified for verification included the Fetch, Velocity Acceleration over the building, Velocity Deficit, and Cavity Flow. Subsequent research flagged the horizontal leeside building eddies and the reattachment zone as additional features worth verifying. Each feature was defined as follows:

FETCH: Airflow upwind of the subject building. For the Urban Study, this airflow was sampled by the southwest tower. A pre-requisite for the validation data was to have all Fetch Tower wind directions sampled (10 m and 2 m AGL) as Westerly (+/- 44 degrees).

VELOCITY ACCELERATION OVER THE BUILDING: An airflow feature where the wind speed of the Roof-4.5 m exceeds that of the SW-10 m.

VELOCITY DEFICIT: An airflow feature where wind speed at NE-10 m level is less than at the equivalent Fetch flow height of10 m (SW-10 m).

CAVITY FLOW: A vertical airflow feature where wind direction of NE-10 m is approximately 180 degrees opposite from NE-2 m. For example, when NE-10 m is 225 (+/-44 degrees) then NE-2 m would be 45 (+/- 44 degrees). Figure 3 shows this feature photographically.

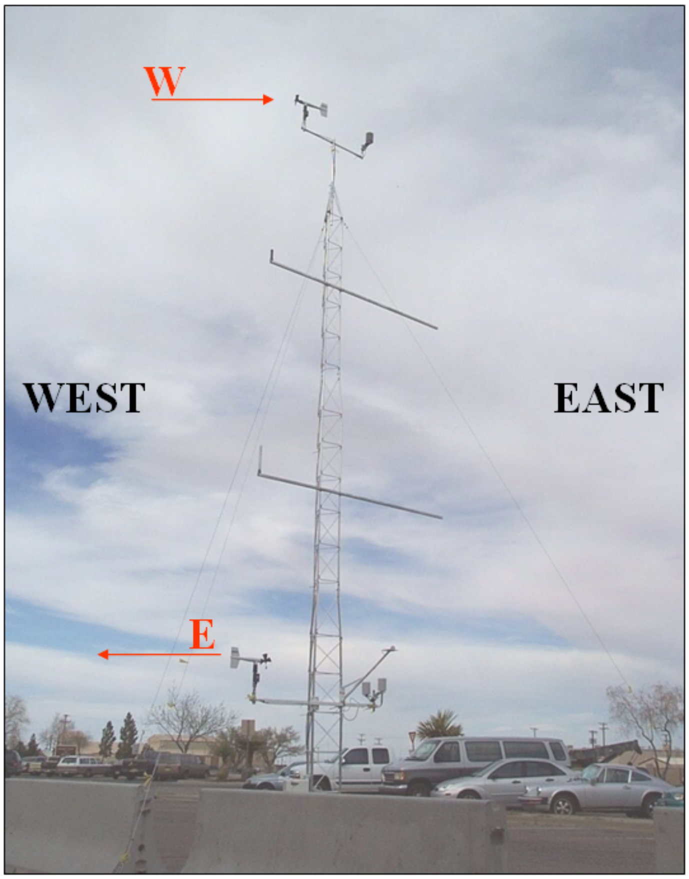

FIGURE 3. The building's leeside Cavity Flow was displayed by the Wind Monitor orientations on the NorthEast tower. While air flow at 10 m AGL was from the west (westerly), airflow at 2.5 m AGL was from the east (easterly).

HORIZONTAL LEESIDE BUILDING EDDIES: For the north-side horizontal leeside eddy, an airflow feature where the leeside wind direction closest to the building structure is basically Southerly (+/- 44 degrees). For the south-side horizontal eddy, the leeside airflow feature wind direction closest to the building is basically northerly (+/- 44 degrees). See Appendix A.

REATTACHMENT ZONE: A leeside-building airflow feature where wind direction is once again consistent with the upwind Fetch Flow. For this Study, the Reattachment Zone wind direction was expected to be westerly (+/- 44 degrees).

6. Case Comparison of wind tunnel verses real-sized building-structure airflow features.

6.1 Selecting categories and cases for study.

Wind flow during the two week data acquisition periods came from all directions. The prevailing wind direction for the Urban Study region and climate (selected season) was westerly (from 270 degrees; where 0 degrees is north). For comparison purposes, only the time periods in which the Fetch Tower airflow was westerly (+/-44 degrees) were considered as potential cases for validating flow features. This wind direction restriction was imposed on both the 10 m and 2 m Fetch Tower levels. [It should be reiterated that once the Fetch Tower recorded a consistent westerly wind, the building structures surrounding the subject building would quickly channel this westerly wind into a southwesterly flow over the building.]

Examining the Fetch Tower's westerly-restricted data, the 'validation' dataset was further subdivided into three categories according to the following wind speed thresholds: 0–2 m/s (both levels), 2–4 m/s (both levels), greater than 4 m/s (both levels). The wind tunnel model used a power law velocity profile with an exponent of 0.16. The range of wind speeds reported by the 'real' Fetch Tower sensors went from 0–15.7 m/s. In all but 1% of the samples considered, the 10 m wind speeds were greater than the 2 m wind speed.

A wind tunnel provides a well-established, steady airflow, whereas the natural atmosphere is quite variable. However, during the New Mexico 'windy' season, having a single location report a period of 10 min or more at a given velocity range occurs frequently. In fact, at the Fetch Tower (westerly wind direction only), for wind speeds less than 2 m/s at both the 2 m and 10 m levels, there were three uninterrupted 20–21 min periods. For Fetch Tower wind speeds [WS] between 2 and 4 m/s (2 m/s =< WS < 4 m/s) at both levels, there were 2 cases which reported 12 min durations. For Fetch Tower winds greater than 4 m/s at both levels, 6 cases of 30 min and greater, were identified. This later category reported one period of 261 min (4 hr 8 min) in which the velocities at the southwest Fetch Tower (both levels) were consistently greater than 4 m/s.

For statistical purposes, the total number of minutes fitting each category, the longest duration observed, and the cases are tabulated in the following table:

TABLE 2. Summary of the 'Real' Fetch Tower data that is most closely equivalent to a wind tunnel scenario.

-FETCH TOWER- WESTERLY WINDS	WS < 2 m/s	2 m/s =< WS < 4 m/s	WS > 4 m/s
Total minutes in this wind speed range	443	220	789
Longest Duration (min)	21	12	261
Cases Considered	3 (> 20min)	2 (> 10min)	6 (> 30 min)

Five Tower Data: Data for the 11 potential cases were extracted from the five towers used in the *WSMR 2003 Urban Study* data set. No changes had to be made to the 'WS < 2 m/s' category. However, the 'WS between 2 and 4 m/s' category, had untimely holes in the coincident north and roof tower data files. After re-examining the westerly Fetch Tower data with wind speeds between 2 and 4 m/s, a qualifying 5-min period was identified and data was retrieved from *all* towers. The other incomplete data sets were retained for supportive evidence.

All the 'WS > 4 m/s' cases had some non-Fetch Tower data absent during their periods. In that there were no qualifying periods in which all the towers reported data, the three cases selected were considered as one.

6.2 Results for 'westerly winds < 2 m/s' category.

6.2.1 Background: Three cases of 20-21 minute duration were analyzed. These cases occurred on Julian Dates 84 (1900–1919 Local Time [LT]) and 85 (0026–0046 LT; 0555–0614 LT). The ambient conditions for these evening, midnight, and morning cases included minor (~0.3 mb)

Pressure trends increasing and the latter two cases deceasing. Relative humidity was steady and in the upper 30% for the evening case, and between 60–70% for the midnight and morning cases. The range of solar radiation recorded during the morning case was from 0 to 22 W/m^2 (South Tower). Stability was neutral. Temperatures for the three cases were approximately 15.5 °C, 9.5 °C, and 7.8 °C, respectively.

6.2.2 General wind pattern: In general, the 10 m level winds exceeded the 2 m level winds. A minor exception was recorded at the N tower during the morning case.

6.2.3 If one were to describe the velocity magnitudes in ascending order, the general tower/level order would place the NE-2 m data at the base with the slowest magnitudes, followed by the SW-2 m AGL winds at a slightly increased velocity. This pattern was consistent for all three cases. As for the top end of the wind speed range, all towers, both levels, during the morning case reported wind speeds less than 2 m/s. In contrast, the evening and mid-night cases reported several magnitudes above 2 m/s from the Roof, S-10 m and N-10 m tower data. In the next sections, the wind characterization with respect to the airflow features will be described.

6.2.4 Validation Data: The following discussion describes the airflow character for each validation feature within the WS < 2 m/s category.

6.2.4.1 **Fetch (WS<2 m/s):** As per Category requirement, Fetch Flow tower winds were westerly and less than 2 m/s in magnitude at both the 2 m and 10 m levels.

6.2.4.2 **Velocity Acceleration over the building (WS<2 m/s):** All three cases reported an accelerated flow. Using an average of the SW-10m wind speeds as a reference, the average acceleration or velocity increase by case was about 33% (evening), 31% (midnight), and 19% (morning).

6.2.4.3 **Velocity Deficit (WS<2 m/s):** All three cases reported a Velocity Deficit feature. The evening and morning cases reported a Velocity Deficit in 70% and 85% of the data, respectively. The midnight case reported this feature 48% of the case. Average velocity reductions for the three cases were 49% (evening), 18% (midnight), and 38% (morning).

6.2.4.4 **Cavity Flow (WS<2m/s):** Three scenarios were considered when evaluating the Cavity Flow in the NE tower data. These scenarios included NE-10 m wind directions from: the southwest, west and northwest.

When NE-10 m winds were southwesterly, the morning case displayed a leeside Cavity Flow 90% of the time; the evening case reported 15% of the data in a cavity pattern. The midnight case presented a cavity pattern 5% of the time.

The NE-10 m westerly and northwesterly wind direction scenarios yielded a Cavity Flow 10% and less, of the time.

6.3 Results for the ‘westerly winds between 2 and 4 m/s’ category.

6.3.1 Background: Four cases of 12, 12, 5, and 8 min durations were analyzed. These cases occurred on Julian Date 84 (0611–0622 LT, 0628–0639 LT; 1718–1725 LT; 2210–2214 LT). The Roof and North tower data for the first two cases (morning) were missing. The NE tower data were also missing for the evening. The only case with all tower data concurrently available was the nighttime case (2210–2214 LT).

The ambient conditions for all cases consisted of a steady Pressure and Relative Humidity [RH]. RH was in the upper 20% for the morning cases, in the mid-50% for the night case, and in the low 10% for the evening case. The solar radiation for the morning cases reported a steady increase, ranging from 5–55 W/m^2. The evening solar radiation reported a consistent sharp V-shaped dip in

all towers (about 80 W/m^2). Because of the recovery trend in all tower data, this dip could have been cloud or mountain-shadow induced. Temperatures for 3 of the 4 cases were steady at approximately 14 °C (morning), 11 °C (night), and 24 °C (evening). The earlier morning case showed a consistent temperature drop in all tower measurements of just less than 1 °C; followed by a temperature increase.

6.3.2 General wind pattern: All four cases report the 10 m level winds greater than the 2 m level winds. In general, the lowest wind speeds were reported from NE-2 m, with the NE-10 m level reporting the second lowest wind speeds (the Velocity Deficit area). The greatest velocities in the two morning cases tended to be from the S-10 m, with wind speeds exceeding 4 m/s.

The night case had no velocities greater than 4 m/s. Lowest wind speeds from the non-Fetch Towers for this category were from NE-2 m.

The evening case showed the Roof data with the greatest wind speeds (>= 4 m/s). No NE tower data were available for this evening case. Eighty-eight percent of the evening N-2 m data reported values of less than 2 m/s.

A bimodal wind direction distribution was observed from all four cases. The largest wind direction group was within a narrower range than the pre-requisite Fetch Tower boundaries of 225–315 degrees. That is, the reported directions were between 233 degrees to 308 degrees. The second wind direction group was from the NE-2 m tower data, where the wind direction was from the eastern quadrants, between 20 and 138 degrees. Note: The NE tower is where a vertical Cavity Flow was expected.

6.3.3 Validation Data: The following describes the airflow character for each validation feature within the WS between 2 m/s and 4 m/s category.

6.3.3.1 **Fetch (2=<WS<4 m/s):** As per Category requirement, Fetch Flow tower winds were westerly with wind speeds greater than or equal to 2 m/s and less than 4 m/s at both 2 m and 10 m levels.

6.3.3.2 **Velocity Acceleration over the building (2=<WS<4 m/s):** Two cases provided the required Roof data. In the nighttime case, 40% of the data showed a slight (5%) acceleration over the roof. All data in the evening case reported Velocity Acceleration. On average there was a 27% increase in velocity for this latter case.

6.3.3.3 **Velocity Deficit (2=<WS<4m/s):** Three of the four cases showed a Velocity Deficit. The evening case was missing data from the NE tower and could not be evaluated. Two of the cases reported this feature in 100% of the data. The third case showed the velocity deficit in 92% of the data. The percent decrease with respect to the averaged-10m Fetch Flow velocity was between 24-45%.

6.3.3.4 **Cavity Flow (2=<WS<4 m/s):** As with the earlier category, three scenarios were considered when evaluating the Cavity Flow in the NE tower data. These scenarios included NE-10 m wind direction from: the southwest, west and northwest.

When NE-10 m winds were southwesterly, the morning cases displayed a leeside Cavity Flow 67% and 75% of the time; the night case presented a cavity pattern 25% of the time. The Northeast tower data was missing in the evening case, so it could not be evaluated.

The westerly NE-10 m airflow yielded the best cavity pattern. The two morning cases showed a cavity in 50% and 100% of the data, respectively. The night westerly NE-10 m airflow case results were identical to the southwesterly NE-10 m airflow, reporting a cavity 25% of the time. No NE tower data was available for the Evening case.

The northwesterly NE-10 m airflow scenario reported no cavity pattern in any cases.

6.4 Results for 'westerly winds greater than 4 m/s' category.

6.4.1 Background: Three cases qualified for this category. These cases were 58, 35, and 249 min in duration. These cases occurred on Julian Dates 83 (1554–1651 LT, 1726–1800 LT) and 85/86 (2358–0406 LT). The Roof and North tower data for the first two cases (afternoon and evening) were missing. The NorthEast tower data were missing for the last case (night). With no case providing data from all towers, the category character had limited results.

The ambient atmospheric conditions for the afternoon and evening cases reported a steady Pressure and RH. Over the approximately 4 hr period of the night case, all towers showed a Pressure drop of almost 4 mb and, a brief 3% RH drop over about 20 min followed by a 4% RH increase over the remaining 3.5 hr. The solar radiation for the afternoon case reported a brief dip of approximately 12 W/m^2, after which a typical late afternoon decrease occurred, ranging from 220–100 W/m^2 over about 44 min. This decreasing trend continued in the evening case, where there was an approximately 35 W/m^2 drop over about 30 min. As expected, no radiation values were reported in the night case. All towers in the afternoon and evening cases reported a Temperature decrease, with the 10 m levels being cooler than the 2 m levels. The NE-2 m level consistently reported the warmest temperatures for the afternoon and evening cases. The coolest afternoon temperatures were from SW-10 m, but were unclear for the evening case. The night case showed an overall cooling trend from all towers.

6.4.2 General wind pattern:

All three cases reported the 10 m level winds greater than the 2 m level winds. In general, there were two WS ranges: the lowest wind speeds (1–4 m/s) were reported by NE-2 m; the second grouping (4–13 m/s) consisted of all the other tower data. Within this second group, the NE-10 m competed with SW-2 m and N-2 m for the lowest wind speeds (4–8 m/s). The greatest velocities by case were at S-10 m for the afternoon (12.6 m/s) and evening cases (12.0 m/s), and at the Roof for the night case (18.5 m/s). Note: Roof data was only available for the night case.

The general wind direction pattern had a bi-modal distribution. One group was between 222–360 degrees, and the second was from the eastern quadrants between 0–150 degrees (with one stray point at 198). NE-2 m data generated the eastern quadrant group, with all of the other towers contributing to the first group.

The night case had no NE tower data, and the wind direction distribution for all towers/levels was between 231–312 degrees. This night case fell well within the pre-request wind direction of 226–314 degrees.

6.4.3 Validation Data: The following describes the airflow character for each validation feature within the WS greater than 4 m/s category.

6.4.3.1 **Fetch (WS>4 m/s):** As per Category requirement, Fetch Flow tower winds were westerly with wind speeds greater than 4 m/s at both the 2 m and 10 m levels.

6.4.3.2 **Velocity Acceleration over the building (WS>4 m/s):** The only case with Roof data was the night case. In the night case, 92% of the data showed accelerated flow over the roof. On average, the velocity increase was 23%.

6.4.3.3 **Velocity Deficit (WS>4 m/s):** The morning and evening cases showed a Velocity Deficit pattern in 100% and 97% of the data, respectively. Missing data from the NE tower prohibited the night case from being evaluated. The velocity reduction with respect to the averaged 10m Fetch Flow data was approximately 31%.

6.4.3.4 **Cavity Flow (WS>4 m/s):** The three scenarios considered when evaluating the Cavity Flow in the NE tower data included NE-10 m wind direction from: the southwest, west and northwest.

When NE-10 m winds were southwesterly, the afternoon and evening cases displayed a leeside Cavity Flow 44% and 54% of the time; no northeast tower data were available to evaluate the night case.

The westerly NE-10 m airflow scenario showed a cavity pattern in the afternoon (72%) and evening (86%) cases. No NE tower data was available for the night case.

The northwesterly NE-10 m airflow scenario reported a cavity pattern in 5-9% of the afternoon and evening cases. No NE data was available for the night case.

6.5 Results summarized by categories and their respective cases.

The following tables summarize the four primary airflow features discussed in the previous section.

TABLE 3. Results of flow features found in the WS< 2 m/s Category. [Julian Day=JD]

Category: WS<2 m/s	**JD#84: evening (1900–1919 LT)**	**JD#84: midnight (0026–0046 LT)**	**JD#85: morning (0555–0614 LT)**
Fetch	Yes	Yes	Yes
Velocity Acceleration	Yes, 75% of time, 33% Acceleration	Yes, 91% of time, 31% acceleration	Yes, 80% of time, 19% acceleration
Velocity Deficit	Yes, 70% of time, 49% decrease	Yes, 48% of time, 18% decrease	Yes, 85% of time, 38% decrease
Cavity Flow–SW [*NE-10 m SW wind scenario]	Yes, 15% of time	Yes, 5% of time	Yes, 90% of time
Cavity Flow–W [+NE-10 m W wind scenario]	Yes, 10% of time	Yes, 5% of time	No
Cavity Flow–NW [#NE-10 m NW wind scenario]	Yes, 5% of time	No	No

TABLE 4. Results of flow features found in (2 =<WS< 4 m/s) Category.

Category: 2=<WS<4 m/s	**JD#84: morning (0611–0622 LT)**	**JD#84:morning (0628–0639 LT)**	**JD#84: night (2210–2214 LT)**	**JD#85: evening (1718–1725 LT)**
Fetch	Yes	Yes	Yes	Yes
Velocity Acceleration	Unknown, No roof data	Unknown, No roof data	Yes, 40% of time, 5% acceleration	Yes, 100% of time, 27% acceleration
Velocity Deficit	Yes, 92% of time, 24% decrease	Yes, 100% of time, 45% decrease	Yes, 100% of time, 31% decrease	Unknown, No NE Tower data
Cavity Flow–SW*	Yes, 67% of time	Yes, 75% of time	Yes, 25% of time	Unknown, No NE Tower data
Cavity Flow–W+	Yes, 50% of time	Yes, 100% of time	Yes, 25% of time	Unknown, No NE Tower data
Cavity Flow–NW#	No	No	No	Unknown, no data

TABLE 5. Results of flow features found in the WS>4 m/s Category.

Category: WS>4 m/s	**JD#83: afternoon (1554–1651 LT)**	**JD#83: evening (1726–1800 LT)**	**JD#85: night (85/2358–86/0406 LT)**
Fetch	Yes	Yes	Yes
Velocity Acceleration	Unknown, No roof data	Unknown, No roof data	Yes, 92% of time, 23% acceleration
Velocity Deficit	Yes, 100% of time, 30% decrease	Yes, 97% of time, 32% decrease	Unknown, NE data unavailable
Cavity Flow–SW*	Yes, 44% of time	Yes, 54% of time	Unknown, NE data unavailable
Cavity Flow–W^{+}	Yes, 72% of time	Yes, 86% of time	Unknown, NE data unavailable
Cavity Flow–NW$^{\#}$	Yes, 5% of time	Yes, 9% of time	Unknown, NE data unavailable

7. Building leeside, horizontal side-eddy feature.

The validation of the leeside, horizontal side-eddy feature is shown graphically and photographically in Appendix A. Data for this feature was taken from *WSMR 2005 Urban Study*. Note that for the northern horizontal side eddy, the air flow source begins from the west (channeled between buildings), curls around (flowing north to south, then south to west), and by the time it encounters the wind sensor, the airflow direction is from the south. The picture of the yellow flags tied to fence posts assists in the visualization of this horizontal side eddy.

The southern leeside, horizontal side-eddy feature follows a mirror image of the northern side-eddy pattern. That is, in the southern side-eddy, the channeled flow is from the west then curls toward the north, then west, and finally encounters the wind sensor with a northerly (from the north) wind direction.

8. Reattachment zone.

The reattachment airflow is shown graphically in Appendix A. As per the initial requirements, the Fetch airflow was westerly; therefore, the reattachment airflow was also observed as westerly.

9. Summary and recommendations.

The goal of this research was to validate a physical model with real data. This was done by isolating and identifying airflow patterns occurring within the physical model, selecting sensors to best quantify these airflow features, extracting optimal measurement placement from the model runs, and comparing data from a real-sized scenario with that of the miniaturized physical model.

The physical model selected consisted of a single miniaturized office building and simulated atmospheric airflow around and above the building. The airflow remained steady; however, the miniaturized building was varied in height-width dimensions, as well as orientation. These model 'runs' were conducted in the EPA/NOAA Wind Tunnel and the results were published by Snyder and Lawson in 1994. Specific characterizing airflow features were extracted from the results for validation with real data. These features included the Fetch Flow, the Velocity Acceleration over the Roof, the Velocity Deficit, and the Cavity Flow. [In a separate study, the Horizontal side-eddy and Re-attachment Zone flow features were also subjected for verification.]

The optimal 'real' world sensor placement required a meticulous translation of millimeter-scale wind tunnel modeling into the meter-sized real world scaling, as well as a calculated systematic adjustment for non-perpendicular 'real world' wind flow. The field test designed to validate the flow features was conducted in 2003, in New Mexico. The data acquired utilized RM Young Wind Monitor sensors on four 10 m-towers

placed on each side of a single office building and one 5 m tower on the Roof. The results from the 'real'-sized field study not only confirmed the existence of each airflow feature, but also re-enforced our concept that the sensor placement had been optimal for the season in which the data were acquired.

Expanding the investigation to include an urban atmospheric characterization effort, each feature was further examined under three different wind speed categories. These categories kept the pre-requisite that data being evaluated must have a Fetch Tower wind direction of westerly (most closely imitating the wind tunnel scenario). The categories came from subdividing the qualifying validation data into periods when the Fetch Flow had: Wind Speed [WS] <2 m/s, WS between 2–4 m/s, and WS>4 m/s. Three and four cases were identified for each category.

The results were as follows: First, all cases showed 10m wind speeds greater than the 2 m wind speeds. The Acceleration of Velocity over the roof was evident in all three categories. For the two categories of WS less than 2 m/s and greater than 4 m/s, the average velocity accelerated between 19–33%. The WS between 2–4 m/s had one case (evening) which also fell within those percentages, and one case (night) which was much less.

The Velocity Deficit was found in all cases evaluated. Six of the ten cases analyzed showed the feature in 92-100% of the case data. The average velocity decrease was between 18–49%.

The Cavity Flow was present in all wind speed categories. Because earlier research had observed some periodicity in this feature, the Cavity Flow was subdivided into three scenarios which included NE-10 m wind directions that were: southwesterly, westerly, and northwesterly.

When the wind source (Fetch Flow) was categorized as less than 2 m/s, the most consistent evidence (90% of case) of a Cavity Flow was the morning case with NE-10 m winds from the southwest. Otherwise, the occurrence was 15% and less.

When the wind source (Fetch Flow) was categorized as between 2–4 m/s, the most consistent Cavity Flow case (100%) was a morning case with NE-10 m winds from the west. The other cases with winds from the west and southwest showed a Cavity Flow in 25–75% of the data. There was no case evidence of a cavity in the NE-10 m northwest scenarios.

When the wind source (Fetch Flow) was categorized as greater than 4 m/s, the most consistent case (86%) was an evening case with NE10 m winds from the west. The other cases with winds from the west and southwest showed a Cavity Flow in 44–72% of the data. The northwest NE-10m scenario showed a Cavity Flow 5–9% of the time.

The leeside, Horizontal Side-Eddies were displayed graphically and pictorially. These and the Reattachment Zone feature were quantified with the later *WSMR 2005 Urban Study* dataset.

Each of the targeted airflow features identified in the physical model were quantitatively validated in the 'real world' field data. Additional information is reported in ARL Technical Reports and conference papers, available upon request from the authors.

10. RECOMMENDATIONS:

The initial four airflow features investigated utilized the *WSMR 2003 Urban Study* dataset. A similar dataset was acquired two years later in March 2005. Revisiting the flow features with this alternate dataset would enhance understanding of the airflow patterns.

Finally, the next step is to design and implement a field study aimed at validating a computational urban wind field model. This would involve additional towers and sensors placed at new strategic locations. At the time of this writing, ARL was in the process of including a model verification effort in their *WSMR 2007 Urban Study*.

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APPENDIX A: Horizontal Side Eddies and Reattachment Zone Flow Features.

The following figures demonstrate the Horizontal Side Eddies and Reattachment Zone flow features graphically and photographically during the *WSMR 2005 Urban Study*. In Figure A1, the leeside Horizontal Side Eddy on the northeast corner of the building is mapped by the yellow flags tied to the fence posts at approximately 2 m. The ultrasonic anemometer is placed on the final leg of the vortex pattern. Thus, the presence of the Horizontal Side Eddy would be noted when the fetch flow is westerly (from the west) and the ultrasonic pictured reports southerly winds.

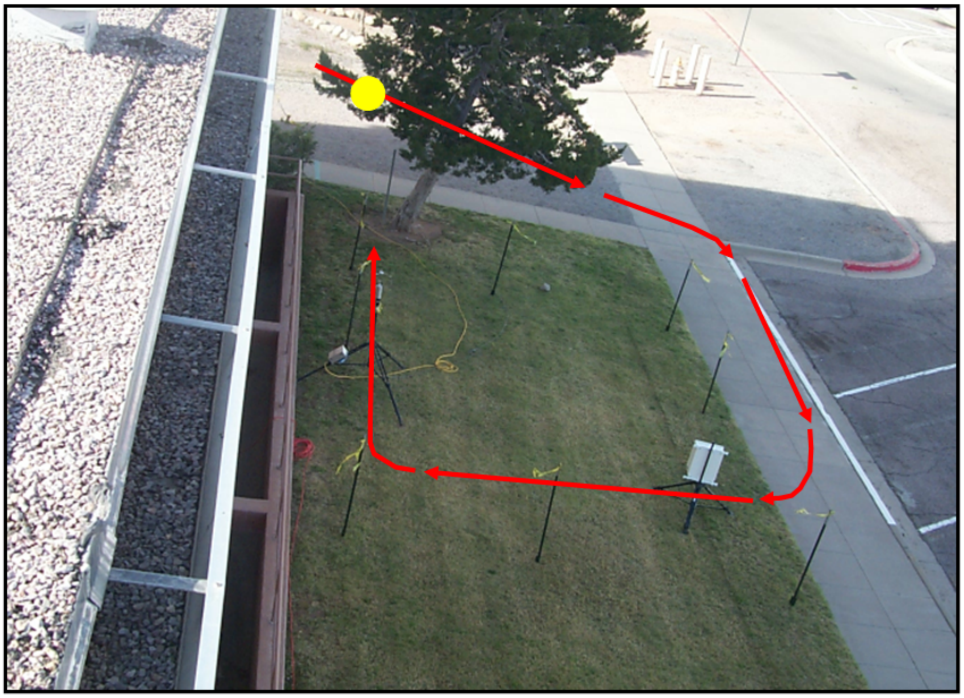

FIGURE A1. Leeside Horizontal Side Eddies: Airflow on the northeast building corner (leeside) was mapped by yellow flags on fence posts and an Ultrasonic Anemometer. This flow went from west to east, turned north to south, then east to west and finally south to north. An Ultrasonic Anemometer was positioned along the final leg of the eddy.

In Figure A2, the time series shows two unique patterns. Between 0300-0900 hours LT, the leeside Reattachment Zone is reporting southeasterly flow (loosely dashed blue line). When this southeasterly flow encounters the building it is channeled into a steady southerly flow. By 1200 LT, the winds have shifted to a westerly flow and the expected Horizontal Side Eddies form downwind of the building, on both the northeast and southeast corners of the building. The time series data demonstrates this flow pattern by showing the final leg of the northeast eddy (corner vortex) as southerly/from the south (solid red line); and, the final leg of the southeast eddy (corner vortex) as northerly/from the north (tightly dashed green line).

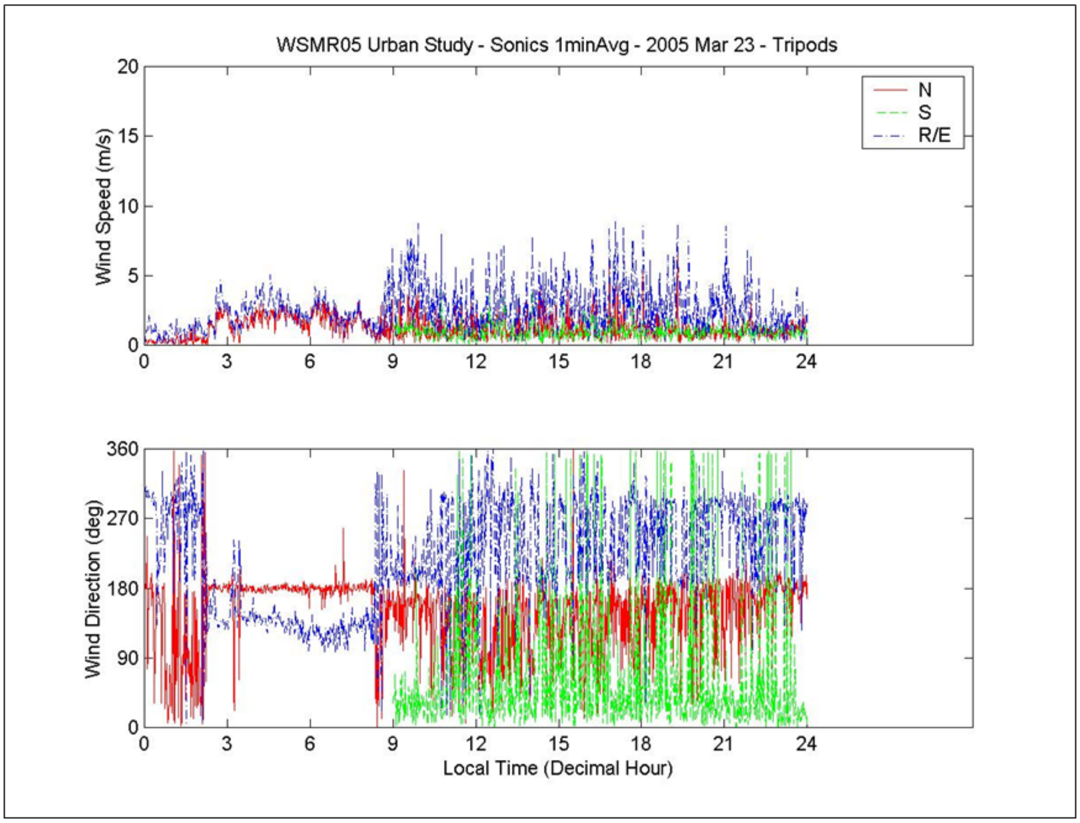

FIGURE A2. The northeast Leeside Horizontal Side Eddy data (N), the southeast Leeside Horizontal Side Eddy data (S) and the Re-attachment Zone data (R/E) are displayed in this 24 hr time series plot of Wind Speed and Direction.